THE NATIONAL
SHIPBUILDING
RESEARCH PROGRAM

FINAL REPORT

EVALUATION OF HIGH-STRENGTH STEELS PRODUCED BY ADVANCED METALLURICAL PROCESSES

THE MARITIME ADMINISTRATION OF THE DEPARTMENT OF TRANSPORTATION IN COOPERATION WITH SP-7, THE WELDING RESEARCH PANEL OF THE SHIP PRODUCTION COMMITTEE, SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS, AND THE AMERICAN BUREAU OF SHIPPING

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FOREWORD

This report presents the results of a research and development project initiated by the Ship Production Committee of the Society of Naval Architects and Marine Engineers and financed through a cost-sharing contract between the U.S. Maritime Administration, Newport News Shipbuilding and Drydock Corporation, the American Bureau of Shipping, and Ingalls Shipbuilding, Incorporated. The principal objective was to identify and characterize steels produced by advanced steelmaking and on-line processing techniques and possessing high strength and toughness and superior weldability.

This report was conducted under the Ship Production Committee SP-7 Welding Research Panel chairmanship of Mr. B. C. Howser, and SP-7 program management of Mr. M. J. Tanner, both of Newport News Shipbuilding. Publication of the report was under SP-7 chairmanship of Mr. Lee Kvidahl and SP-7 program management of Mr. Ovide J. Davis, both of Ingalls Shipbuilding, Incorporated, under Maritime Administration Cooperative Agreement Contract MA-11989.

The program was carried out by the American Bureau of Shipping under the direction of Mr. I. L. Stern. Mr. M. Wheatcroft was the project manager; Dr. D. Y. Ku and Mr. W. Hanzalek served as project engineers, and Mr. R. F. Waite supervised the laboratory testing.

In addition, the suppliers of the test materials are acknowledged: Nippon Kokan Kabushiki Kaisha, Sumitomo Metal Industries Ltd., Lukens Steel Company, and Newport News Shipbuilding.

EXECUTIVE SUMMARY

Newly developed high-strength steels produced by advanced steelmaking techniques and thermomechanical processing are shown to have toughness and weldability superior to those of conventionally heat treated, quenched and tempered steels. The above was confirmed by small-scale toughness testing and by controlled thermal severity testing to determine heat-affected zone cracking susceptibility. Small-scale testing of shielded metal arc weldments was also conducted.

In view of their superior toughness and weldability these newly developed high strength steels should be useful for applications such as low temperature ship service, offshore structure service especially in harsh environments, and as a potential replacement for HY80/100 steels.

1.0 BACKGROUND:

Increased stength of steels used for ship stuctural applications have traditionally been achieved with higher alloy content. Depending on the alloying elements chosen, the increased strength is achieved at a cost in weldability and toughness.

Recent developments in the control of properties through precise thermomechanical processing (control of rolling temperature regimes, rolling thickness reductions and cooling rates) and advanced steelmaking techniques, have led to the creation of steel with increased strength and toughness, while maintaining modest carbon equivalents to provide good weldability. There is reason to believe that excellent results will be attainable with the new families of high strength steels which are now or are expected to become commercially available in the near future. A more detailed description of the metallurgical processing is included in Appendix C.

It is expected that the use of the new high strength steels will prove attractive in many marine applications, because of their potential relative insensitivity to heat input, HAZ hardening, and their potential for reduced requirements for preheat.

Data generated in a current SP-7 project studying high heat input effects on 50 ksi yield strength steels produced by thermomechanical processing has indicated superior notch toughness and resistance to heat input(1). Data in the technical literature has indicated similar promise for higher yield strength steels.

2.0 OBJECTIVE:

The immediate objective of this investigation was to explore the potential advantages of new high strength (65 to 120 ksi yield) steels produced by advanced steelmaking and on-line processing techniques for marine applications.

A longer term objective is to facilitate the introduction to the shipbuilding industry of the new high strength steels processed by advanced on-line processing techniques with toughness and weldability properties beyond those currently available.

3.0 ACHIEVEMENT:

The study has provided a preliminary characterization of newly developed steels with yield strengths varying from 65 ksi to 120 ksi. On the basis of the preliminary data obtained, it appears that by use of advanced metallurgical processes, high strength steels can be produced which provide improved toughness and weldability; the alloying elements required for such steels could be substantially lower than that required for conventionally processed quenched and tempered steels of the same strength and toughness levels.

4.0 APPROACH:

Candidate steels over the strength range of interest which were being made by thermomechanical controlled rolling with on line cooling were obtained from two producers. In addition, a fourth steel produced by conventional quench and temper techniques was included. Each steel was subjected to appropriate tests to indicate tensile, Charpy V-Notch, NDT (drop weight) and dynamic tear properties. Controlled thermal severity (CTS) testing was also conducted to provide preliminary information as to weldability.

Small-scale weldments of sample steels selected by means of evaluation of previous base metal and CTS test results were produced and tested.

5.0 BASE MATERIAL SELECTION:

On the basis of commercial availability, the target properties of the candidate steels as manufactured by thermomechanical rolling and on-line cooling are as follows:

Target Properties

Candidate Steel Source	Thickness, in inches	Minimum Yield Strength, in ksi	Minimum Charpy V-Notch, in ft-lb	Maximum IIW Carbon Equivalent
A	1.25	65	100 at -75C	0.40
B	2.00	65	100 at -75C	0.40
C	2.00	80	30 at -60C	0.50
D	2.00	100	30 at -60C	0.60

Arrangements for samples indicated that the material from Source B would not be available in the time required. Accordingly, a substitute steel was introduced. This was a high strength steel manufactured by conventional quench and temper heat treatment. The yield strength of this Q&T steel was indicated as 80 ksi minimum.

6.0 TESTING PROCEDURES:

6.1 Chemical Analysis

The composition of the four candidate steels and the two HY steels used in the weldability test (see 6.4 below) was determined.

6.2 Metallography

The microstructure and austenitic grain size were determined for each candidate steel at three locations: surface, quarter-thickness, and mid-thickness.

6.3 Mechanical Testing

6.3.1 Tensile Test

Longitudinal and transverse tensile properties were determined with 1/2" diameter, 2" gage length specimens removed from the quarter-thickness location.

6.3.2 Charpy V-Notch Test

Longitudinal and transverse Charpy V-Notch impact properties were determined with standard-sized specimens removed at three locations: surface, quarter-thickness, and mid-thickness.

6.3.3 NDT Drop Weight Test

The nil-ductility transition (NDT) temperature was determined with 5/8" thickness specimens with the weld bead located at the plate surface for all steels, at the quarter-thickness location for Steels B/C/D, and at the mid-thickness location for Steel A.

6.3.4 Dynamic Tear Test

The dynamic tear energy was determined with longitudinal 5/8" thickness specimens removed from the plate surface.

6.3.5 Hardness Survey

A through-thickness hardness survey was conducted for each candidate steel.

6.4 Weldability Test

Preliminary data concerning the weldability of the four candidate steels was obtained on the basis of Controlled Thermal Severity (CTS) tests (2). The data is presented as an HAZ cracking rating; i.e. the number of HAZ cracks observed by 100X examination of four metallographic sections taken through each test weld. Each test assembly consisted of one bithermal weld (thermal severity number of 16) and one trithermal weld (thermal severity number of 24). In general, two test assemblies were used for each evaluation. The pertinent welding parameters are shown in Table E1. For comparison purposes, CTS tests were conducted with HY80 and HY100 steels.

6.5 Small Scale Weldment Test

Steel A and Steel C were selected for the welding (by SMAW) and testing of small-scale weldments. The pertinent welding parameters are shown in Table E2. Testing consisted of transverse tensile, Charpy V-notch and hardness at the quarter thickness where practicable.

7.0 RESULTS:

The results of tests are shown as follows:

Chemical Composition	:	Table One
Metallography	:	Table Two and Figures One through Three
Tensile Properties	:	Table Three and Tables D1/D2 (Appendix D)
Charpy V-Notch Properties	:	Figures Four through Seven and Tables D3/D4/D5 (App. D)
NDT Temperature	:	Table Four
Dynamic Tear Properties	:	Figure Eight and Table D6 (Appendix D)
Hardness Survey	:	Figure Nine and Table D7 (Appendix D)
CTS Test	:	Table Five
Small-Scale Weldment	:	Tables Six through Eight

8.0 DISCUSSION OF RESULTS:

8.1 Steel A

8.1.1 Composition

Steel A is a microalloyed carbon-manganese steel with a very low carbon content (0.04%). The microalloying elements present are columbium, titanium and boron. The carbon equivalent (0.32) easily met the target value, 0.40 maximum.

8.1.2 Metallography

The average McQuaid-Ehn austenitic grain size was eight (8). The accepted requirement for fine grain steel is five (5) or finer.

Determinations taken at the mid thickness indicated a grain size of seven (7), slightly coarser than at other locations.

The microstructure consisted of bainite and ferrite as shown at Figure One, 500X magnification. The microstructure was uniform through the thickness of the plate. The sulfide inclusions were spheroidal, typical of shape-control processing.

8.1.3 Tensile Properties

The yield strength determined for the longitudinal and transverse orientations met the target value of 65 ksi minimum. The transverse tensile and yield strength determinations were somewhat higher than the values determined in the longitudinal orientation. The reason for this is not apparent.

8.1.4 Charpy Impact Properties

Steel A showed a lower bound Charpy V-notch temperature transition between approximately -100F and -120F. The lower bound curve indicates that the steel met the target value, 100 ft-lbs at -75C (-103F). The lower bound was comprised of data points from all (three) locations, in contrast with Steels C and D where the lower bound was defined almost exclusively by surface data. It is interesting to note that Steel A has been accelerated cooled, while Steels C and D have been directly quenched and tempered. The upper shelf data was over 170 ft-lbs.

The Charpy V-notch data meets the ABS MODU requirement for special application service at -30C, i.e., 25 ft-lbs at -60C.

8.1.5 NDT Drop Weight Test

The nil-ductility transition (NDT) temperature was -65C (-85F) at the plate surface. This temperature corresponds to the near upper shelf regime for Charpy V-notch and to the transition range for dynamic tear. The mid-thickness NDT temperature was slightly lower, -75C (-103F), and corresponds to the dynamic tear lower shelf.

8.1.6 Dynamic Tear Test

Steel A exhibited dynamic tear energies over 1100 ft-lbs at temperature down to -60C, where a very steep transition occurred. The transition range correlated with the surface nil-ductility transition temperature as determined by the drop-weight test.

8.1.7 Hardness Survey

Steel A showed minor variations in hardness on a through thickness traverse. The hardness ranged from 93 to 98 in the Rockwell B Scale. The value of 98 was recorded only at the plate surface.

8.1.8 CTS Test

No CTS testing was conducted for Steel A, 1-1/4" thickness, in that the yield strength and the thickness did not permit correlation to the HY80/100, 2" thickness, used for a comparison basis, and a steel of comparable yield strength and thickness was not available.

8.1.9 Small Scale Weldment

Steel A exhibited generally satisfactory although somewhat irregular results. The tensile strength was approximately 4-1/2% below that previously recorded for the base metal; however it was noted that the fracture occurred in the weld metal and not in the

base metal. With the exception of one fusion-line specimen the Charpy V-notch impact data met the ABS MODU requirement for weldments for special application service at -30C; i.e. 17 ft-lb at -60C. The Charpy V-notch impact data was somewhat lower (especially two fusion-line specimens) than the previously determined base metal data indicating a degradating effect of the heat of welding. Subsequent metallographic examination indicated that the fracture path for the 10 ft-lb specimen was contained wholly within the weld metal adjacent to the fusion line, and that the fracture path for the 17 ft-lb specimen generally followed the fusion line although it did at some locations pass solely through the weld metal adjacent to the fusion line.

The above results suggest that the low tensile strength and Charpy V-notch impact values recorded for Steel A were resultant from the weld metal characteristics and did not indicate substandard performance of Steel A in the small scale weldment test. The Vickers Hardness data showed no abnormally high hardness values.

8.2 Steel B

As previously noted Steel B is a 80 ksi yield strength Q & T steel which has been used as a substitute for the originally intended 65 ksi yield strength thermomechanically processed steel. The test results are evaulated in terms of 80 ksi yield strength target properties noted in Section 5.0 as Candidate Steel C.

8.2.1 Composition

Steel B is a low carbon (0.10%) conventional quenched and tempered carbon-manganese-molybdenum steel with a high

manganese content (1.84%). Columbium is present as a microalloying addition. The carbon equivalent (0.50) met the target value, 0.50 maximum.

8.2.2 Metallography

The average McQuaid-Ehn austenitic grain size was seven (7). The accepted requirement for fine grain steel is five (5) or finer. Determinations taken at three thickness locations indicated that a grain size gradient extended from the surface to the mid thickness where the smallest grain size, eight (8), was observed.

The microstructure consisted of tempered martensite as shown at Figure Two, 500X magnification. No significant differences were noted among the microstructures at the three locations: surface, quarter thickness, and mid thickness. The sulfide inclusions were spheroidal, typical of shape-control processing.

8.2.3 Tensile Properties

The yield strength determined for the longitudinal and transverse orientations met the target value of 80 ksi minimum. The ductility parameters were satisfactory. Steel B met the tensile requirements for HY80.

8.2.4 Charpy Impact Properties

The lower bound Charpy V-notch data met the target value, 30 ft-lbs at -60C (-76F).

Extrapolation of the lower bound to 0F (testing higher than -40F was not conducted) indicates that Steel B also meets one requirement for HY80, 60 ft-lbs at 0F. In addition, the

transverse/mid-thickness data meets the second requirement for HY80, 35 ft-lbs at -120F specified for specimens of transverse orientation and mid-thickness location (for plate thicknesses 7/8" and over). It should be noted, however, that data from many surface/longitudinal and quarter-thickness/longitudinal specimens developed less than 35 ft-lbs when tested at -120F.

The Charpy V-Notch data meets the ABS MODU requirement for special application service at -30C, i.e. 25 ft-lbs at -60C.

8.2.5 NDT Drop Weight Test

The nil-ductility transition (NDT) temperature was -45C (-49F) for the plate surface and also for the quarter-thickness location. This temperature corresponds to the near upper shelf regime of Charpy V-notch data; the lower bound value at the NDT temperature is approximately 100 ft-lbs. The NDT temperature is within the transition for the dynamic tear data.

8.2.6 Dynamic Tear Test

Steel B exhibited dynamic tear energies over 1100 ft-lbs at temperature down to -20C (-4F), where a gradual transition commenced. The approximate mid-point of the transition range correlated with the nil-ductility transition temperature. The dynamic tear data, 800 ft-lbs at -40F, indicates that Steel B will meet the requirement for HY80, 450 ft-lbs at -40F.

8.2.7 Hardness Survey

With the exception of several high values at one surface of the plate, Steel B exhibited a relatively uniform through thickness hardness ranging from 96 to 98 in the Rockwell B Scale. High

values of Rockwell C Scale 27 (approximately 103 in the Rockwell B Scale) were recorded at one surface of the plate; this could be resultant from higher quenching rates at this surface.

8.2.8 CTS Test

Steel B demonstrated greater resistance to HAZ cracking than the base-line HY80 steel when welded in the controlled thermal severity (CTS) test. No HAZ cracking (i.e., a crack rating of zero) was noted for the bithermal test weld with a thermal severity number (TSN) of 16. In comparison the base-line HY80 showed an HAZ cracking rating of one (1). For the trithermal test weld (TSN = 24) Steel B developed an HAZ cracking rating of one (1), while the baseline HY80 exhibited an HAZ cracking rating of four (4).

8.3 Steel C

Steel C was submitted as an 80 ksi yield strength steel. Testing indicated that this steel is a 100 ksi yield strength steel. The test results are evaluated in terms of both 80 ksi and 100 ksi yield strength requirements.

8.3.1 Composition

Steel C is a low carbon (0.12%) thermomechanically processed steel. The principal alloying elements are manganese, nickel, chromium and molybdenum. Vanadium and boron are present as microalloying additions. The carbon equivalent (0.49) met the target values for 80 ksi yield strength (0.50 maximum) and 100 ksi yield strength (0.60 maximum).

8.3.2 Metallography

The average McQuaid-Ehn austenitic grain size was six (6). The accepted requirement for fine grain steel is five (5) or finer. At

the mid-thickness location the grain size was seven (7), slightly finer than at other locations.

The microstructure consisted of tempered bainite and martensite, as shown at 500X magnification in Figure Three. The microstructure was uniform through the thickness of the plate. The sulfide inclusions were spheroidal, typical of shape-control processing.

8.3.3 Tensile Properties

The yield strength determined for the longitudinal and transverse orientations was 106 ksi. This strength met the target property for 100 ksi yield strength steel. The ductility data was satisfactory. Steel C met the tensile requirements for HY100, however the yield strength exceeded the upper limit of the yield strength range specified for HY80, 99.5 ksi..

8.3.4 Charpy Impact Properties

The lower bound Charpy V-notch data met the target value, 30 ft-lbs at -60C (-76F); and met the impact requirements for HY80/100. The Charpy V-notch data also meets the ABS MODU requirement for special application service at -30C, i.e., 25 ft-lbs at -60C.

The lower bound is defined exclusively by transverse specimens removed from the plate surface. In addition, longitudinal/surface data generally represents the lower bound for specimens of longitudinal orientation. The data suggests that the surface toughness is less than the toughness for other plate locations. This is not interpreted as being detrimental in that all Charpy V-notch toughness values were quite high and met requirements and the target values.

8.3.5 NDT Drop Weight Test

The nil-ductility transition (NDT) temperature was determined for the plate surface and for the quarter thickness. The results suggested that the fracture toughness properties of the plate surface are different and lower than those of the quarter thickness. The surface NDT temperature was -29C (-20F) while the quarter thickness NDT temperature was -75C (-103F).

8.3.6 Dynamic Tear Test

Steel C exhibited dynamic tear energy over 1100 ft-lbs at temperature down to -50C (-58F), where a sharp transition commenced. The dynamic tear data indicates that Steel C will meet the requirements for HY80/100: at -40F, 450 ft-lbs (for HY80) and 500 ft-lbs (for HY100).

8.3.7 Hardness Survey

The hardness traverse data was uniform ranging from 21 to 23 in the Rockwell C Scale. No significant variation in tensile strength through thickness of the plate is indicated.

8.3.8 CTS Test

The CTS test results for Steel C were superior to the results for both base-line materials, HY80 and HY100. Steel C developed HAZ cracking ratings of one-half ($\frac{1}{2}$) for the bithermal test weld (TSN = 16) and for the trithermal test weld (TSN = 24).

8.3.9 Small-Scale Weldment

Steel C exhibited satisfactory results. The tensile strength was equivalent to that determined previously for the base metal. All Charpy V-notch impact data met the ABS MODU requirement for weldments for special application service at -30C; i.e. 17 ft-lb at -

60C. The Charpy V-notch impact data was somewhat lower (especially two fusion-line specimens) than the previously determined base metal data indicating a degradating effect of the heat of welding. The Vickers Hardness data showed no abnormally high hardness values.

8.4 Steel D

Steel D was submitted as a 100 ksi yield strength steel. Testing indicated that this steel is a 120 ksi yield strength steel. For comparison purposes the criteria and requirements for 100 ksi yield strength steel are used.

8.4.1 Composition

Steel D is a low carbon (0.11%) thermomechanically processed steel. The principal alloying elements are manganese, nickel, chromium and molybdenum. Vanadium and boron are present as microalloying additions. The carbon equivalent (0.51) easily met the target value for 100 ksi yield strength (0.60 maximum).

8.4.2 Metallography

The average McQuaid-Ehn austenitic grain size was six (6). The accepted requirements for fine grain steel is five (5) or finer. No variation with thickness location was noted.

The microstructure consisted of tempered bainite and martensite, as shown at 500X magnification in Figure Three. The microstructure was uniform through the thickness of the plate. The sulfide inclusions were spheroidal, typical of shape-control processing.

8.4.3 Tensile Properties

The yield strength determined for the longitudinal and transverse

orientations was 124 ksi and 122 ksi, respectively. These values met the target values of 100 ksi, but exceeded the upper limit of the yield strength range specified for HY100, 115 ksi. The ductility data was satisfactory.

8.4.4 Charpy Impact Properties

In general, the Charpy V-notch data met the target value, 30 ft-lbs at -60C (-76F). The transverse/mid-thickness data met the HY100 requirements, 30 ft-lbs at -120F and 55 ft-lbs at 0F, which are specified for specimens of transverse orientation and mid-thickness location (for plate thicknesses 7/8" and over). It should be noted, however, that data from the transverse/surface developed less than 30 ft-lb when tested at -120F. For information, the Charpy V-notch transverse/mid-thickness data meets the requirements for HY130, i.e. (1) 60 ft-lbs minimum at 0F (2) and at 70F, a maximum of the 0F data value plus 15 ft-lbs. The Charpy V-notch data also meets the ABS MODU requirement for 100 ksi yield strength steel for special application service at -30C, i.e., 25 ft-lbs at -60C.

The lower bound is defined almost exclusively by transverse specimens removed from the plate surface; at -120F the value was less than 10 ft-lbs. In addition, longitudinal/surface data generally represents the lower bound for specimens of longitudinal orientation. The- data suggests that the surface toughness is less than the toughness for other plate locations. It is further noted that this lower-toughness surface effect, which for Steels C and D defines the lower bound, is more severe for Steel D than for Steel C in terms of absolute values and in terms of percentage decrease below the average data plots. This suggests

that the severity of the surface effect increases with increasing yield strength.

8.4.5 NDT Drop Weight Test

The nil-ductility transition (NDT) temperature for the surface was -29C (-20F); the NDT temperature for the quarter thickness was -55C (-67F). The surface NDT temperature corresponds to the transition ranges of the Charpy V-notch impact lower bound data and the dynamic tear data. The lower bound Charpy V-notch data at the NDT temperature is approximately 40 ft-lbs. The dynamic tear energy at the NDT temperature is approximately 400 ft-lbs. The quarter-thickness NDT temperature corresponds to the upper transition of the Charpy V-notch impact non-surface data. The difference in the NDT temperatures again suggests that the surface of the plate has a lower toughness than the quarter-thickness location.

8.4.6 Dynamic Tear Test

Steel D exhibited dynamic tear energy over 1100 ft-lbs at temperature down to 0C (32F), where a gradual transition commenced. The dynamic tear data did not meet the requirements for HY100, 450 ft-lbs at -40F however the specimens tested were longitudinal/surface and probably developed a lower absorbed energy than the specified transverse/mid-thickness specimens. For information, the dynamic tear data indicates that Steel D will meet the requirement for HY130, 500 ft-lbs at 0F.

8.4.7 Hardness Survey

The hardness traverse data ranged from 24 to 29 in the Rockwell C Scale. With the exception of several readings of R_C 25 near the

mid thickness of the plate and one high value of R_c 29, the hardness was uniform ranging from 26 to 28 in the Rockwell C Scale.

8.4.8 CTS Test

The CTS test results for Steel D were superior to the results for both base-line materials, HY80 and HY100. Steel D developed an HAZ cracking rating of one-half ($\frac{1}{2}$) for the trithermal test weld (TSN = 24); no cracking was developed for the bithermal test weld.

8.5 Mechanical Property Correlations

8.5.1 Strength and Toughness

The thermomechanically processed steels A/C/D exhibit a decrease in toughness as the yield strength increases. This is shown by the dynamic tear energy-temperature transition (Figure Eight) where the dynamic tear curve shifts to the right with increasing yield strength. The inverse relationship of toughness and yield strength is generally valid for steels that are not vastly different in chemistry. Thus, it is interesting to note that the dynamic tear curve for the conventionally processed quenched and tempered Steel B generally falls with the curve for the thermomechanically processed Steel C although the yield strength of Steel C is over 20 ksi higher than the yield strength of Steel B. This data suggests that the toughness of thermomechanically processed steel is superior to that of an equivalent strength conventionally processed steel.

A comparison of the Charpy V-notch impact absorbed energy-temperature transition (Figures Five and Six) for Steels B and C illustrates that although the energy at -40C is approximately

equivalent, the Steel C transition commences at lower temperature than for Steel B. This indicates a superior low temperature toughness, which is also indicated by the lower nil-ductility transition temperature for Steel C (-103F) than for Steel B (-49F). It should be noted that the above comparisons are based upon "non-surface" data for Steel C, i.e. data from the quarter thickness and from the mid thickness, and all data for Steel B.

8.5.2 NDT, Dynamic Tear and Charpy V-notch

In general, there was not good correlation among the toughness data for the thermomechanically processed steels A/C/D. Nil-ductility transition (NDT) temperature specimens prepared and tested in accordance with ASTM E208 demonstrate that the NDT temperatures are too high for classical correlation to dynamic tear energy-temperature transitions where the NDT temperature corresponds to the lower shelf (4). Comparisons with the Charpy V-notch impact energy-temperature transition also show that the NDT temperatures are too high; although correlation is better with the lower bound curve for Steel D where the lower bound curve is defined by surface specimens. The upper shelf NDT/CVN correlation is documented in the literature (3) although for steels with considerably higher yield strengths.

A more classical correlation between NDT and dynamic tear lower shelf was demonstrated with drop weight specimens prepared with the tension surface and crack-starter weld bead located at the quarter thickness of the plate or at the mid-thickness of the plate. These results, i.e. a lowering of the NDT temperature, was anticipated based upon comparison of surface and non-surface

Charpy V-notch impact data which indicated a lower-toughness surface effect (previously discussed in 8.3.4 and 8.4.4). For Steel C, the absolute value for the Charpy V-notch absorbed energy for the non-surface data at the quarter-thickness NDT temperature and for the lower bound (surface data) at the surface NDT temperature is very similar, approximately 115 foot-pounds. This value is much higher than that generally reported for indexing an NDT/CVN correlation (4)(5). Steel D did not exhibit a CVN correlation similar to Steel C.

Review of all the Charpy V-notch impact test results including absorbed energy, lateral expansion and fracture appearance indicated that the thermomechanically processed Steels C/D displayed a lower-toughness surface effect while the conventionally processed quenched and tempered steel (B) did not exhibit this effect.

9.0 CONCLUSIONS AND RECOMMENDATIONS

On the basis of this study and the results obtained, the following conclusions are drawn.

9.1 All steels studied satisfied the base metal toughness requirements for ABS MODU special application service at -30C.

9.2 Steel B met* the small-scale mechanical test requirements for HY80.

9.3 Steel C met* all (except the HY80 upper limit on yield strength) the small-scale mechanical test requirements for HY80 and HY100, indicating a potential as a substitute for HY steels.

9.4 In the 80 ksi to 100 ksi yield strength range the thermomechanically processed steel exhibited higher toughness

than the conventionally processed quenched and tempered steel.

9.5 Steels B/C/D exhibited greater resistance to HAZ cracking than HY80/100.

9.6 Steels A and C exhibited good weldability and generally met the ABS MODU requirements for special application service at -30C.

9.7 The thermomechanically processed steels exhibited a lower toughness associated with the surface in comparison with other locations. This lower-toughness surface effect was more evident in the direct quenched and tempered steels (C/D).

It is recommended that thermomechanically processed steels of the type evaluated herein be considered for higher strength applications requiring high toughness and for higher strength applications at lower temperature. This recommendation includes further evaluation as outlined below.

10.0 FUTURE WORK

10.1 It is recommended that for Steel C large-scale explosion bulge testing be conducted to procedures and requirements for HY80/100. Explosion bulge testing could serve to evaluate the overall (complete thickness) toughness of the material and the effect, if any, of the plate surface properties.

10.2 It is recommended that evaluation be extended to shipyard applications in areas of line-heating, cold-forming and high heat input welding.

* dynamic tear test data indicates likely compliance with specification requirements.

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APPENDIX A

FIGURES

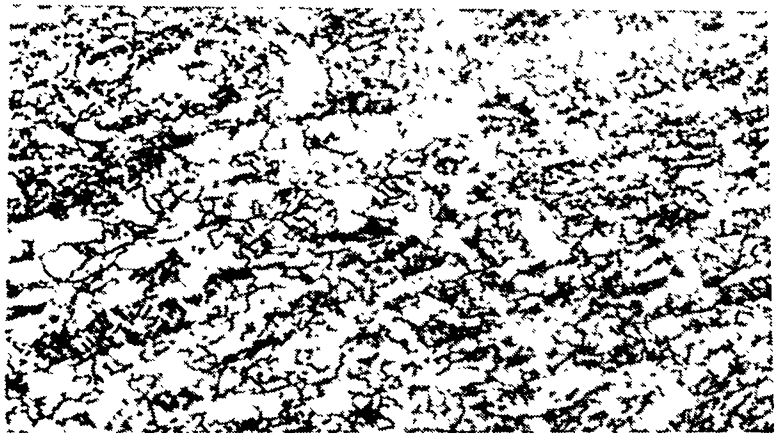

FIGURE 1
Steel A: 500X, 2% Nital etch

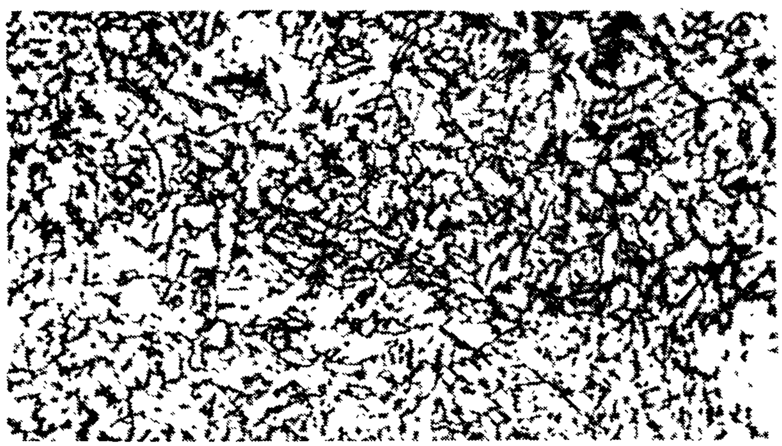

FIGURE 2
Steel B: 500X, 2% Nital etch

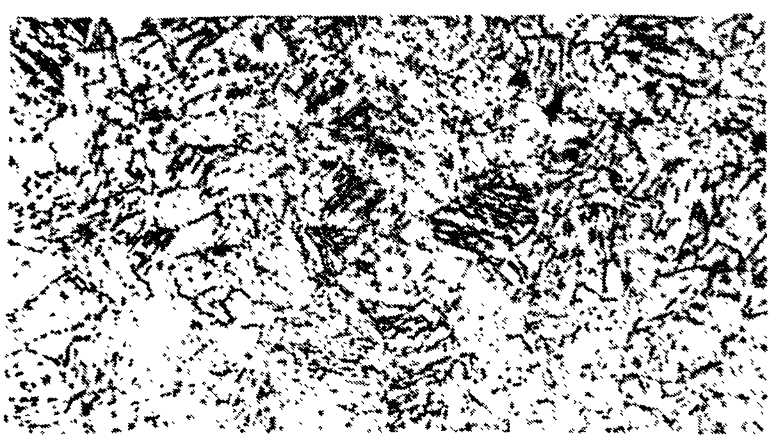

FIGURE 3
Steel C/D: 500X, 2% Nital etch

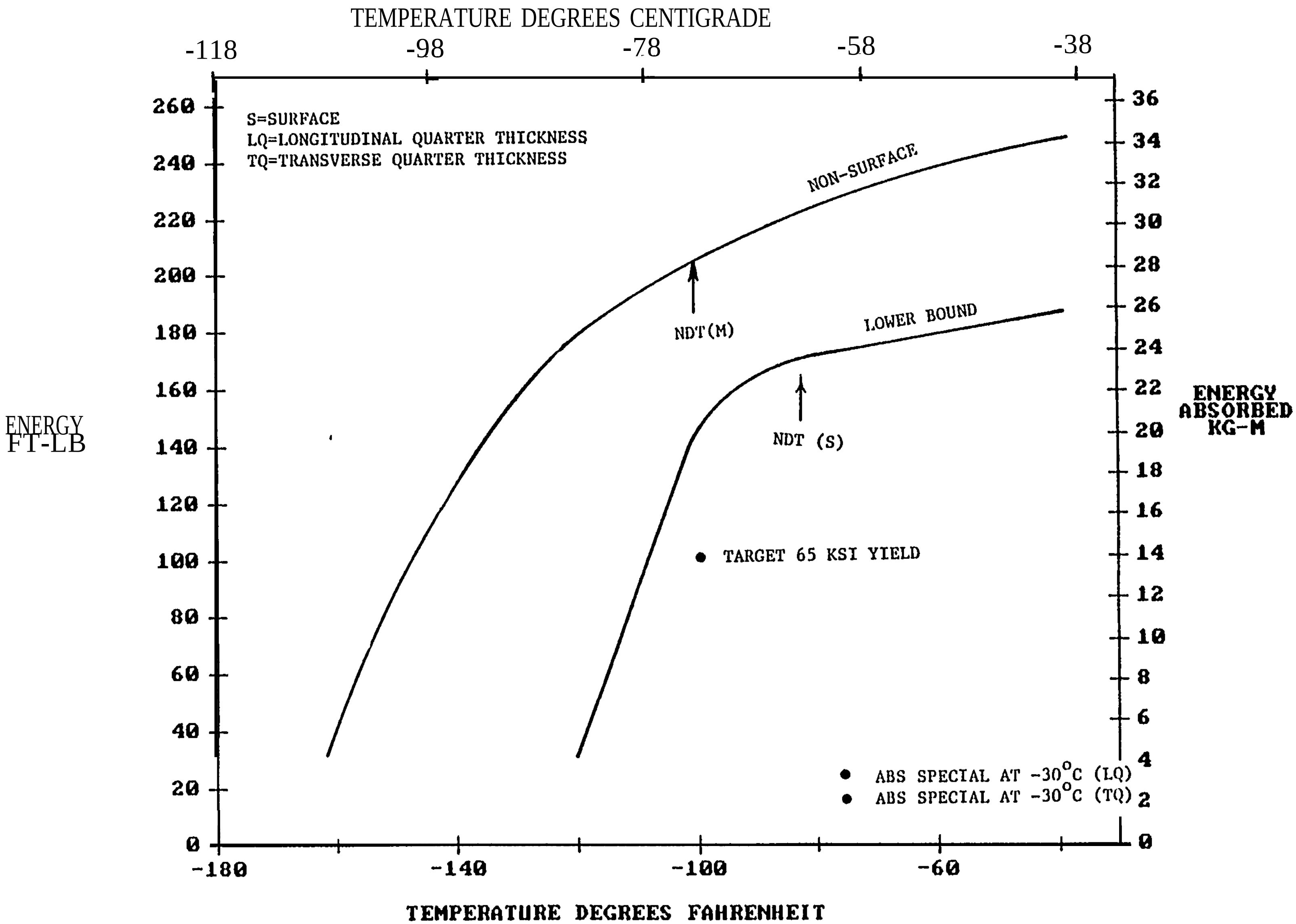

FIGURE FOUR STEEL A
CHARPY V-NOTCH ABSORBED ENERGY
TEMPERATURE TRANSITION

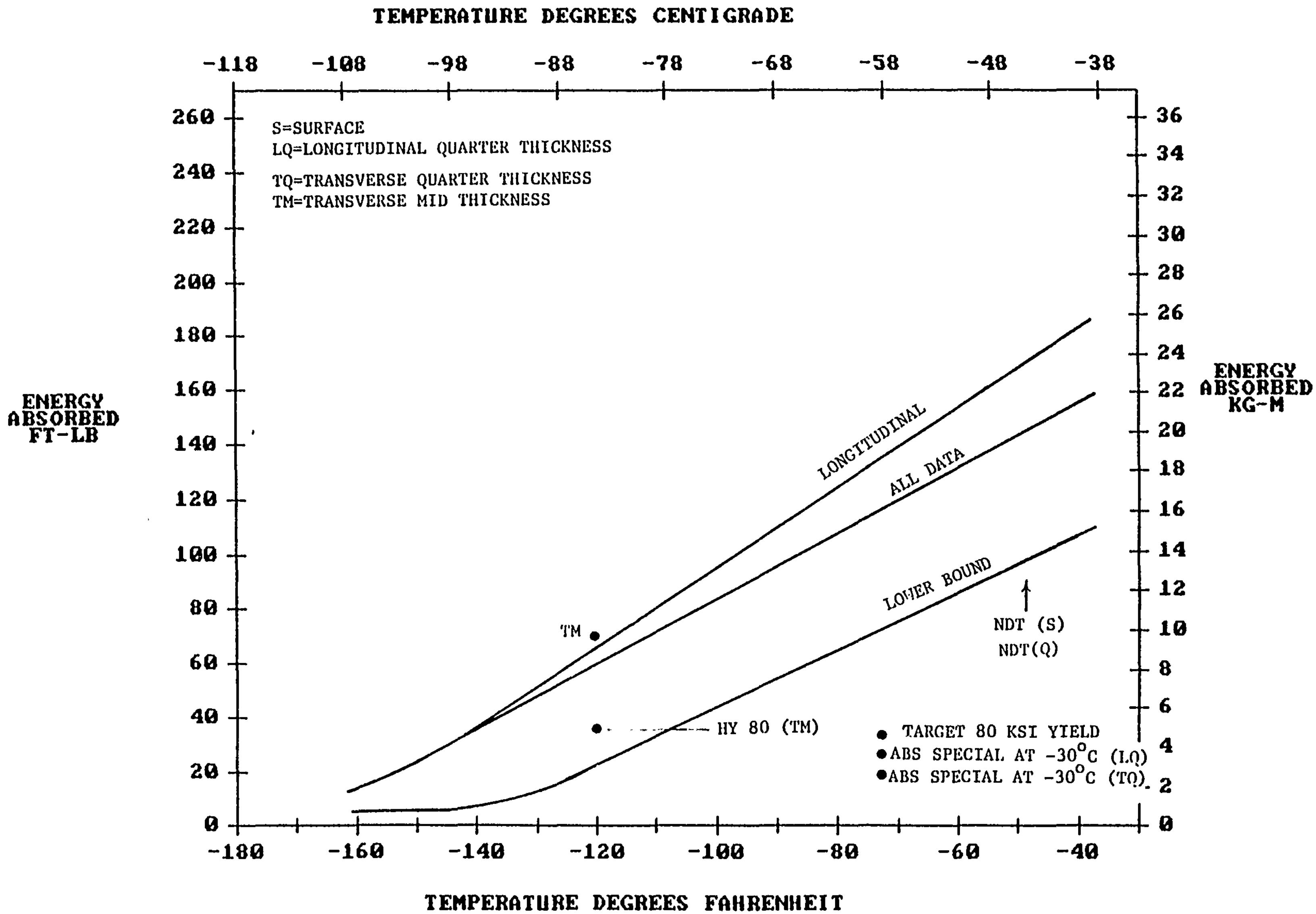

FIGURE FIVE STEEL B
CHARPY V-NOTCH ABSORBED ENERGY
TEMPERATURE TRANSITION

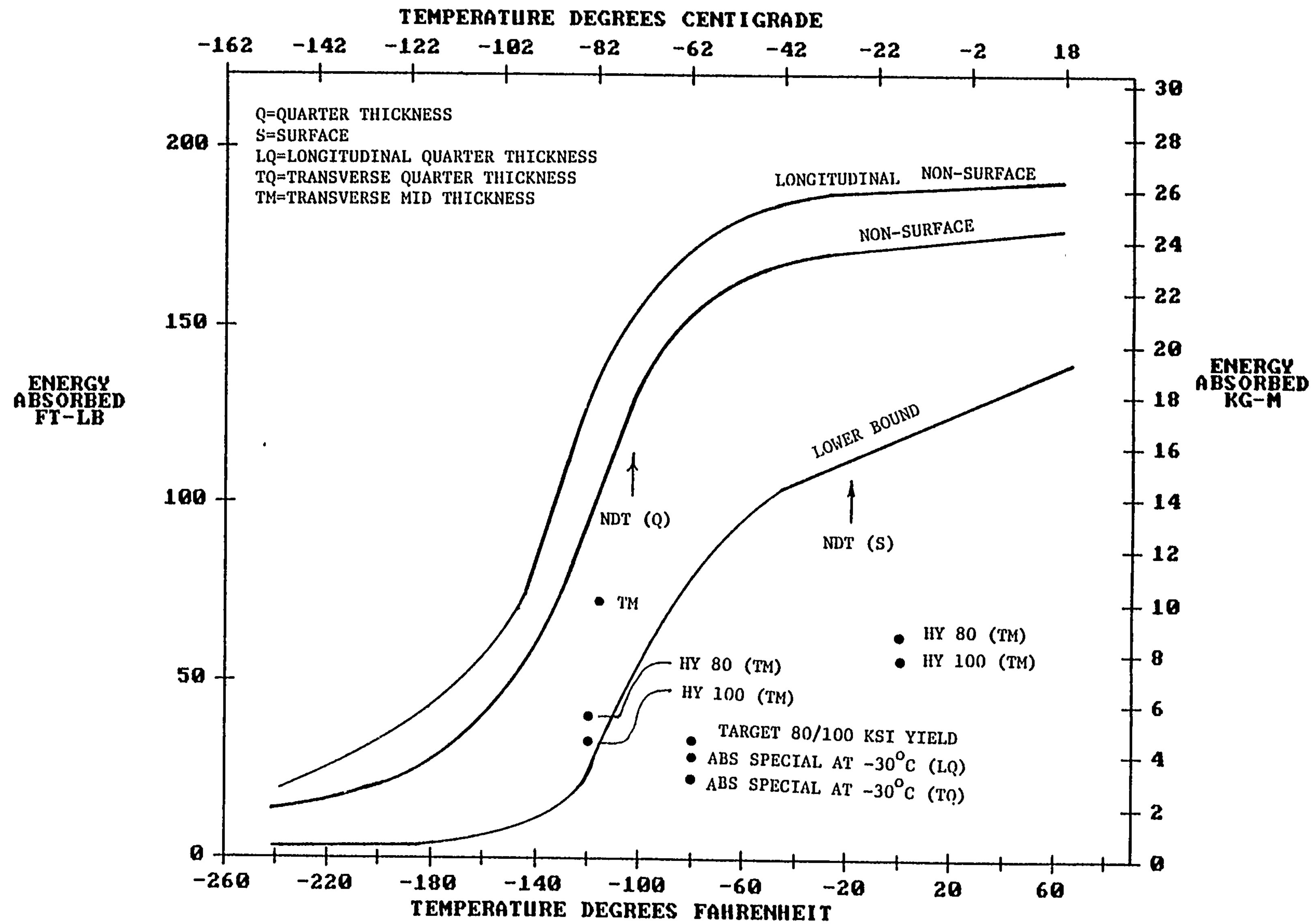

FIGURE SIX STEEL C
CHARPY V-NOTCH ABSORBED ENERGY
TEMPERATURE TRANSITION

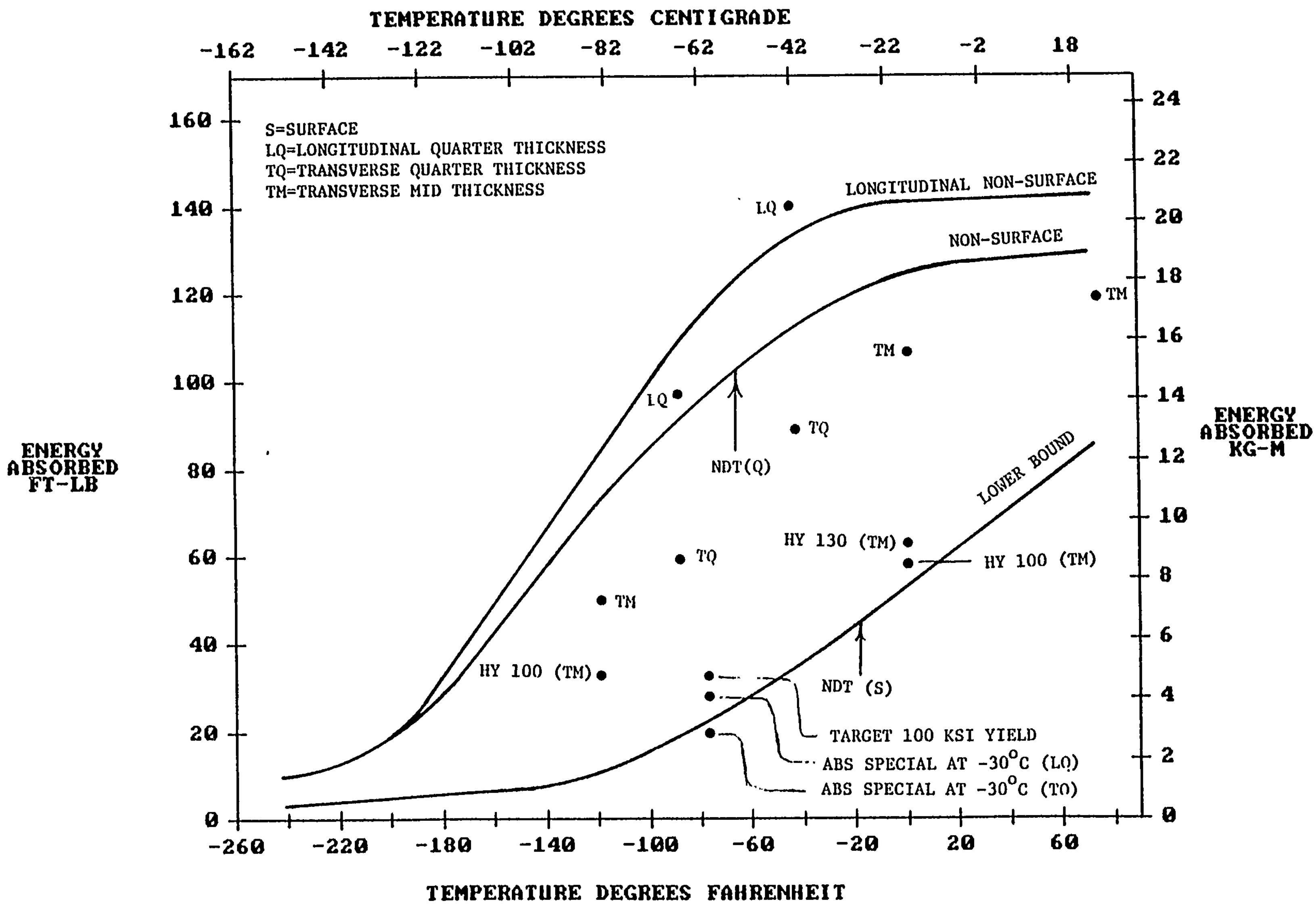

FIGURE SEVEN STEEL D
CHARPY V-NOTCH ABSORBED ENERGY
TEMPERATURE TRANSITION

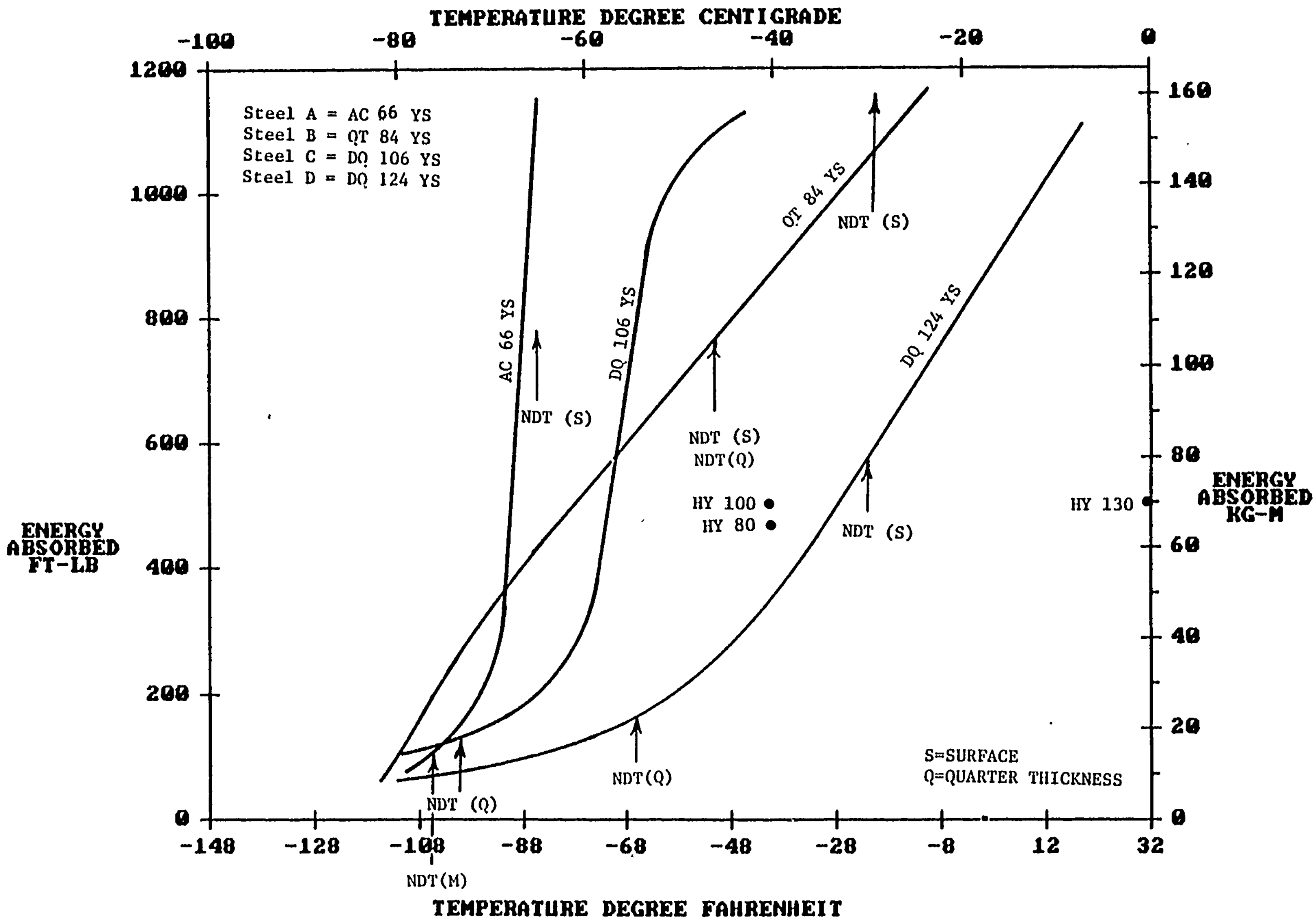

FIGURE EIGHT STEEL A THROUGH D DYNAMIC TEAR ABSORBED ENERGY TEMPERATURE TRANSITION

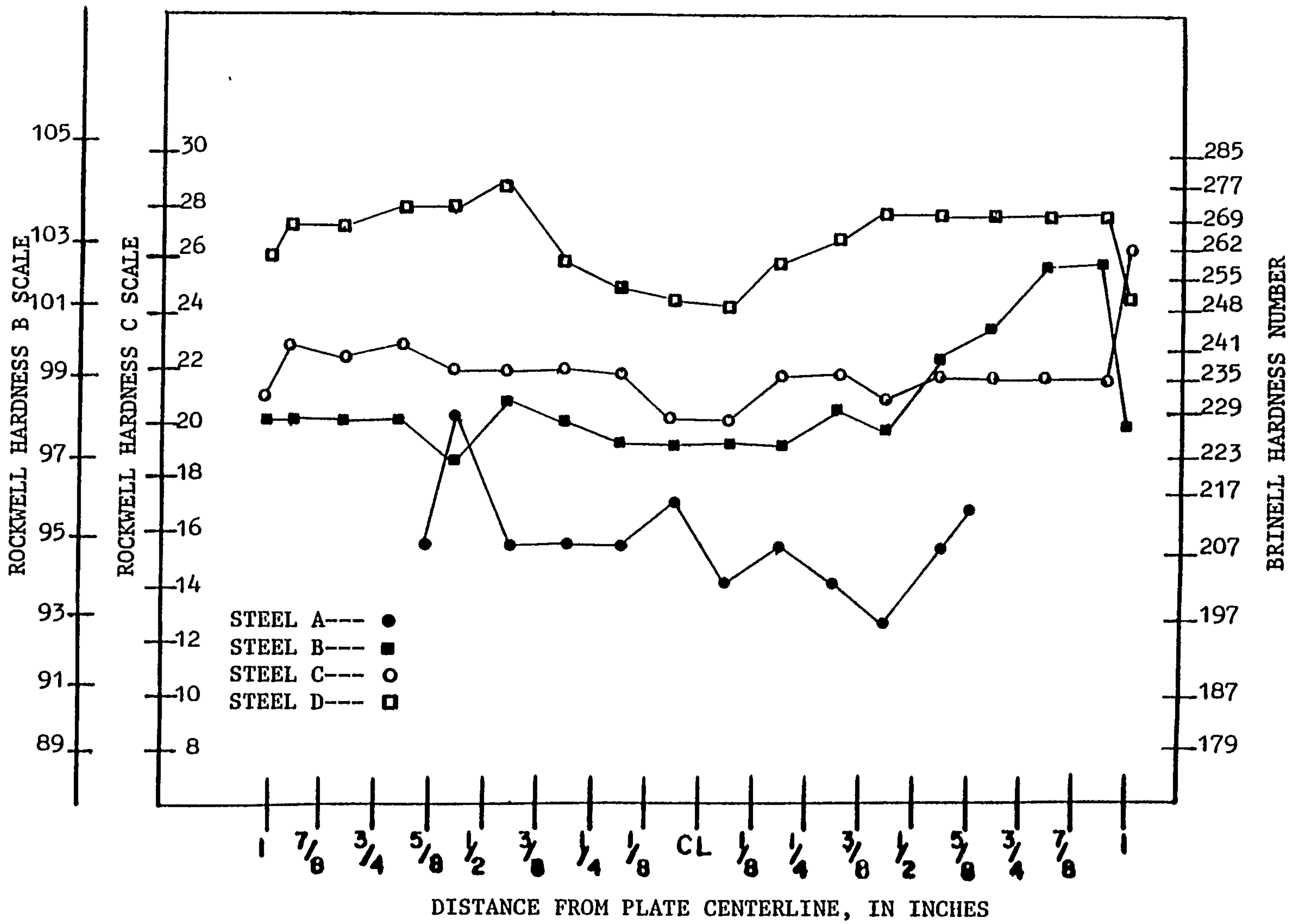

FIGURE NINE

THROUGH THICKNESS HARDNESS SURVEY

APPENDIX B

TABLES

TABLE ONE
CHEMICAL COMPOSITION, IN PERCENT
IIW CARBON EQUIVALENT

ELEMENT	STEEL A	STEEL B	STEEL C	STEEL D	ABS MODU FQ GRADES(1)	CTS TEST CONTROLS HY80	CTS TEST CONTROLS HY100	MIL-S-16216J HY80	MIL-S-16216J HY100
Carbon	0.04	0.10	0.12	0.11	0.18 max	0.16	0.17	0.10-0.20	0.10-0.22
Manganese	1.43	1.84	1.01	0.94	1.60 max	0.35*	0.33*	0.10-0.45	0.10-0.45
Silicon	0.17	0.21	0.27	0.26	0.55 max	0.21*	0.16*	0.12-0.38	0.12-0.38
Phosphorus	0.019	0.012	0.010	0.014	0.025 max	0.14	0.016	0.020 max	0.020 max
Sulfur	0.003	0.005	0.003	0.003	0.025 max	0.017	0.020	0.020 max	0.020 max
Nickel	0.23	0.05	0.78	1.05	(2)	2.67*	2.71*	2.43-3.32	2.67-3.57
Chromium	0.04	0.10	0.45	0.45	(2)	1.61*	1.49*	1.29-1.86	1.29-1.86
Molybdenum	0.01	0.31	0.23	0.33	(2)	0.43*	0.36*	0.27-0.63	0.27-0.63
Copper	0.25	0.10	0.23	0.23	(2)	0.04*	0.10*	0.25 max	0.25 max
Aluminum	0.032	0.046	0.018*	0.049*	---	0.017*	0.005*	NS	NS
Columbium	0.028	0.029	0.005*	0.005*	(2)	0.005*	0.005*	NS	NS
Vanadium	0.005*	0.005*	0.038	0.048	(2)	0.008*	0.005*	0.03 max	0.03 max
Titanium	0.018	0.005*	0.005*	0.005*	---	0.005*	0.005*	0.02 max	0.02 max
Boron	0.0011	0.001*	0.0011	0.0012	(2)	0.001*	0.001*	NS	NS
Nitrogen	0.0026	0.008*	0.005*	0.005*	---	0.003*	0.007*	NS	NS
IIW-CE	0.32	0.50	0.49	0.51		0.81	0.78	1.02 max 0.59 min	1.05 max 0.61 min

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

NS = Not Specified

(1) Alloying and fine-grain elements are to be reported.

(2) Are to be reported, including zirconium.

*By spectrographic analysis

TABLE TWO
AUSTENETIC GRAIN SIZE (1)

SAMPLE	SURFACE	QUARTER THICKNESS	MID THICKNESS
Steel A	8	8	7
Steel B	6	7	8
Steel C	6	6	7
Steel D	6	6	6

(1) A grain size of five or finer (i.e., higher number) fulfills the requirements for "Fine Grain".

TABLE THREE
AVERAGE TENSILE PROPERTIES
LONGITUDINAL (TRANSVERSE)

SAMPLE	TENSILE STRENGTH, IN KSI	YIELD STRENGTH, IN KSI	ELONGATION GL = 4.51 A, IN PERCENT	REDUCTION OF AREA, IN PERCENT
Steel A	91.5 (95.0)	66.0 (70.0)	28 (26)	74 (76)
Steel B	98.0 (97.0)	84.0 (84.0)	25 (24)	76 (72)
Steel C	114 (114)	106 (106)	24 (21)	76 (72)
Steel D	130 (130)	124 (122)	20 (20)	70 (67)

Note: Data for Steels B/C/D (2 inches in thickness) is from quarter thickness. Data for Steel A ($1\frac{1}{4}$ inches in thickness) is from quarter thickness thru mid thickness.

TABLE FOUR
NIL-DUCTILITY TRANSITION TEMPERATURE

SAMPLE	TEST LOCATION	IN DEGREES CENTIGRADE	IN DEGREES FAHRENHEIT
Steel A	Surface	-65*	-85
Steel A	Mid Thickness	-75*	-103
Steel B	Surface	-45*	-49
Steel B	Quarter Thickness	-45*	-49
Steel C	Surface	-29	-20*
Steel C	Quarter Thickness	-75*	-103
Steel D	Surface	-29	-20*
Steel D	Quarter Thickness	-55*	-67

*Temperature scale used in test.

TABLE FIVE
CONTROLLED THERMAL SEVERITY (CTS) TEST
HAZ CRACKING RATING

SAMPLE	BITHERMAL TSN = 16	TRITHERMAL TSN = 24
Steel B	0	1
Steel C	½	½
Steel D	0	½
HY80	1	4
HY100	2	1
HY80 (1)	2	3

(1) Data from Stern/Quattrone (Ref. 2).

TABLE SIX
WELDMENT TRANSVERSE TENSILE (1/4 T) DATA

SAMPLE	TENSILE STRENGTH, IN KSI	LOCATION OF FRACTURE
STEEL A	88.0	WELD METAL
	86.0	WELD METAL
STEEL C	114	BASE METAL
	114	BASE METAL

TABLE SEVEN

WELDMENT TRANSVERSE CHARPY V-NOTCH (1/4 T) DATA, IN FOOT-POUNDS AT -75F (-60C)

SAMPLE	FUSION LINE	1mm HAZ	3mm HAZ
STEEL A	10	148	166
	17	144	178
	132	74	149
STEEL C	155	155	120
	60	118	165
	54	114	166

TABLE EIGHT
WELDMENT TRANSVERSE HARDNESS SURVEY (1/4 T) DATA IN VICKERS HARDNESS NUMBER

LOCATION	STEEL A	STEEL C
WELD METAL CENTERLINE	223	250
FUSION LINE	237	265
DISTANCE FROM FUSION LINE, IN mm:		
1	211	239
2	191	226
3	182	256
4	195	248
5	202	243

APPENDIX C

COMMENTARY ON METALLURGICAL PROCESSING

Commentary on Metallurgical Processing

Three of the four steels investigated herein have been produced by thermomechanical processing. Through thermomechanical processing, steel can be produced to levels of toughness and strength usually achieved by a separate heat treatment subsequent to rolling. A leaner chemistry without loss of strength is possible; thus reducing the carbon equivalent with an attendant increase in weldability (A1). Economic benefits are derived from lower alloying costs and omission of heat treatment. (A2)

Thermomechanical processing is an extension of the controlled rolling technology, a viable commercial practice for more than fifteen years. The basic change from controlled rolling methodology is the rolling of the steel at lower temperature, specifically around the Ar_3 temperature. Thermomechanical processes are proprietary and as such show differences in the number of rolling stages and the reduction ratio of each stage, the temperature regimes of the rolling stages, and the use or omission of accelerated cooling or direct quench and tempering after rolling. The use of accelerated cooling or direct quench and tempering after thermomechanical rolling permits steel chemistries of much lower carbon equivalent without loss of strength properties (A2). In addition, some proprietary processes may include substantial intermediate reheating and continued rolling (A3).

In light of the proprietary differences inherent to the thermomechanical processing of steel, several generalizations as to the process can be made and are listed below:

1. The slab reheat temperature is generally lower than for conventional steel rolling practice; reheat in the range of 950-1200C (1742-2192F) provides a finer initial austenitic grain size at the beginning of rolling than the higher temperature of conventional practice (A4).

2. The subsequent rolling stages consist of high reductions in the austenite recrystallization region to promote a finer austenitic grain size, and high reductions in the austenite non-recrystallization region but above the austenite transformation temperature to promote deformation bands for subsequent fine grain nucleation (A4, A5). In addition to the above rolling stages, rolling may also be conducted just above the Ar3 and at times below the Ar3 after which the steel is air cooled (A4, A5, A6, A7).

3. Depending upon the desired properties the rolled steel is air cooled, accelerated cooled or direct quenched and tempered. Generally, the cooling rates for accelerated cooling are less that 15C per second while for direct quenching they are higher (A8, A9, A10).

The cooling practices used for the thermomechanical processed steels tested herein are as follows:

Steel A	-	Accelerated Cooled
Steel C	-	Direct Quenched and Tempered at 640C (1184F).
Steel D	-	Direct Quenched and Tempered at 600C (1112F).

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A4. "SSC, Sumitoma's Special Controlled Rolling Process" May 1980.

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A7. "Kawasaki Thermomechanical Rolling Process for Improvement of Notch Toughness", Kawasaki Steel Company.

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A9. Sogo, Y., et al "A New Thermomechanically Treated 50 Kgf/mm^2 Steel for Welded Structure" Nippon Steel Corporation, October, 1982.

A10. Tsukada, K., et al, "Development of YS 36 Kgf/mm^2 Steel with Low Carbon Equivalent Using On-Line Accelerated Cooling (OLAC)," Nippon Kokan Technical Report, Overseas No. 35 (1982).

APPENDIX D

TEST DATA

TABLE D1

BASE METAL LONGITUDINAL TENSILE PROPERTIES

SAMPLE	TENSILE STRENGTH IN KSI	YIELD STRENGTH IN KSI	ELONGATION GL = 4.51 A, IN PERCENT	REDUCTION OF AREA IN PERCENT
Steel A	91.0, 91.5	66.0, 66.0	27, 29	74, 74
Steel B	97.0, 98.0	83.5, 84.5	24, 26	77, 75
Steel C	114, 113	106, 106	23, 24	76, 76
Steel D	130, 131	123, 124	20, 20	72, 69

TABLE D2

BASE METAL TRANSVERSE TENSILE PROPERTIES

SAMPLE	TENSILE STRENGTH IN KSI	YIELD STRENGTH IN KSI	ELONGATION GL = 4.51 A, IN PERCENT	REDUCTION OF AREA IN PERCENT
Steel A	94.5, 95.5	70.0, 69.5	26, 27	76, 75
Steel B	96.5, 97.0	83.0, 84.0	24, 24	73, 71
Steel C	114, 114	106, 106	21, 21	72, 71
Steel D	128, 131	121, 123	20, 20	68, 66

TABLE D3
BASE METAL CHARPY V-NOTCH PROPERTIES
ABSORBED ENERGY, IN FOOT-POUNDS

SAMPLE	TEST TEMPERATURE IN DEGREES FAHRENHEIT	LONGITUDINAL ORIENTATION SURFACE LOCATION	LONGITUDINAL ORIENTATION QUARTER THICKNESS LOCATION	LONGITUDINAL ORIENTATION MID THICKNESS LOCATION	TRANSVERSE ORIENTATION SURFACE LOCATION	TRANSVERSE ORIENTATION QUARTER THICKNESS LOCATION	TRANSVERSE ORIENTATION MID THICKNESS LOCATION
Steel A	-40	PB*,238,218	PB*,PB*,PB*	PB*,PB*,PB*	186,166,192	259,233,237	187,173,189
	-90	178,247,PB*	PB*,PB*,PB*	PB*,165,180	180,214,238	198,PB*,PB*	163,PB*,PB*
	-120	168,197,209	149,176,PB*	235,38,142	29,33,69,221.5	144,PB*,203	133,PB*,PB*
	-140	189,170,210	183,187,190	PB*,61.5,18,19	104,187,192	151,13,19	123,17,190
	-160	14.5,17,9.0	51.0,9.0,240	11.0,13.0,9.0	15.5,114,138	23.0,14,13	18.0,9.5,205
Steel B	-40	152,183,196,166	197,192,196,193	209,184,204,177	124,141,132,127	102,113,110,126	120,131,125,147
	-50	152,186,146	147,130,155	197,190,189	113,112,104	113,128,119	128,111,112
	-60	194,188,131	120,143,143	124,143,143	121,110,132	94,113,116	120,109,112
	-90	121.5,114,129	107,135,125	107,141,127	95,100,105	106,82,105	107.5,99,69
	-120	48,110,20,20	30,20,27,126	117,109,12,75	71,71,58	68.5,81,72	80,66,65
	-140	32,60,59	7,39,44	34,52,103	73,42,65	69,65,48	16,59,80
	-160	9.5,15,12	26.5,12,10.5	8.5,29,21	19,13,31	60.5,68,17	21.5,30,12.5
Steel C	68	185,178,174	191,188,188	182,189,185	136,177,178	159,181,178	163,183,180
	0	173,178,174	180,188,188	176,189,185	116,150,122	153,165,151	153,154,154
	-40	156,150,149	176,166,181	183,172,189	105,103,108,111	148,155,144	132,151,136
	-90	127,149,165,134	185,140,152	142,130,135	91.5,75,77	123,101,107	137,111,108
	-120	93.5,94,102	117,125,106	99,123,101	56,18,66	58.5,69,61	67,62,97
	-180	14.5,13.5,11.0	13.5,52,11.0	46.5,57,78	6.5,34,20	47.0,23,18.5	39.5,30,56
	-240	9.5,13.5,12.5	9.0,46,31	18.0,11.5,13.5	4.0,9.0,7.5	6.0,9.0,9.5	4.5,8.5,21
Steel D	68	145,135,147	141,147,141	142,142,167	83.5,92,91	114,110,116	117,114,123
	0	120	135	138	56	100	108
	-20	114,133,120	139,151,140	139,151,143	42,85,70	90,104,104	95.5,90,111
	-40	100,101,132	150,135,145	147,142,147	55,64,64	70,99,112	98,99,113
	-50	83,116,115	118,151,147	103,151,143	39.5,52,56	76,88,89	80.5,94,86
	-90	96.5,87,78.5	112,81,91	130,95,106	44.5,43,40	72.5,50,56	72.5,66,17
	-120	68,8,57	75,76,71	76.5,84,66	8.0,29,28	49,54,55	61,53,42
	-180	27,10,10	46.5,7,21	43,12,25	6.5,12,18.5	33,27,26	33.5,36,26
	-240	3	7	10.5	6	9	12.5,16.5

PB = Partial break

Note: *Maximum test machine capacity 264 ft-lbs.
Data for information only: not valid according to ASTM E23.

TABLE D4
BASE METAL CHARPY V-NOTCH PROPERTIES
LATERAL EXPANSION, IN MILS

SAMPLE	TEST TEMPERATURE IN DEGREES FAHRENHEIT	LONGITUDINAL ORIENTATION SURFACE LOCATION	LONGITUDINAL ORIENTATION QUARTER THICKNESS LOCATION	LONGITUDINAL ORIENTATION MID THICKNESS LOCATION	TRANSVERSE ORIENTATION SURFACE LOCATION	TRANSVERSE ORIENTATION QUARTER THICKNESS LOCATION	TRANSVERSE ORIENTATION MID THICKNESS LOCATION
	-40	PB,95,90	PB,PB,PB	PB,PB,PB	91,89,100	81,94,95	93,98,96
Steel A	-90	97,95,PB	PB,PB,PB	PB,96,99	96,96,99	89,PB,PB	96,PB,PB
	-120	86,106,101	86,99,PB	89,32,82	22,26,52,106	82,PB,98	79,PB,PB
	-140	93,108,100	85,97,96	PB,49,14,13	62,94,101	89,10,18	71,16,103
	-160	13,16,11	41,10,98	6,17,9	9,84,PB	14,11,11	11,9,99
	-40	85,87,96,95	89,95,96,94	80,90,95,95	74,82,94,82	68,80,74,81	78,81,82,89
Steel B	-50	88,96,95	86,90,99	90,95,95	73,76,75	80,81,83	88,76,76
	-60	94,96,92	79,44,98	88,92,95	82,77,88	64,75,85	83,69,76
	-90	82,80,91	76,91,90	75,93,90	73,67,69	73,61,77	77,72,50
	-120	30,13,13	18,26,22,96	80,81,16,56	48,50,42	45,61,52	59,46,46
	-140	12,50,42	7,29,32	26,40,72	52,27,44	42,51,36	10,40,60
	-160	2,8,10	15,10,8	3,20,14	10,11,16	39,30,9	15,23,7
	68	81,92,91	87,97,96	92,100,101	79,90,88	87,94,83	88,93,93
Steel C	0	87,92,91	89,97,96	89,100,101	81,91,81	87,94,83	84,97,95
	-40	91,90,85	89,91,92	93,86,98	71,57,68,73	85,86,86	75,86,86
	-90	82,88,77,76	92,83,84	80,83,83	56,50,48	74,65,65	79,70,63
	-120	60,57,67	71,66,67	61,70,60	34,6,39	34,44,42	40,35,60
	-180	8,9,7	8,34,6	24,36,48	0,22,11	29,11,06	23,20,36
	-240	0,6,4	0,29,20	6,4,10	0,4,0	0,3,4	0,2,10
	68	84,76,82	81,88,82	79,74,88	56,61,63	73,74,71	71,74,80
	0	70	77	80	35	62	65
Steel D	-20	68,68,72	80,86,82	60,82,81	27,54,45	57,52,64	70,60,65
	-40	62,63,76	90,81,96	81,85,85	31,34,38	47,50,68	60,56,70
	-50	50,71,72	80,84,88	64,94,85	28,33,36	46,57,62	52,56,58
	-90	55,57,57	66,56,60	77,58,70	27,30,26	41,32,36	41,40,18
	-120	42,9,36	43,47,44	44,55,41	0,19,18	25,32,34	32,32,26
	-180	15,3,4	27,2,7	23,6,11	0,8,14	17,19,14	14,25,18
	-240	2	0	2	0	0	0, 4

PB = Partial break.

TABLE D5
BASE METAL CHARPY V-NOTCH PROPERTIES
FRACTURE APPEARANCE, IN PERCENT SHEAR

SAMPLE	TEST TEMPERATURE IN DEGREES FAHRENHEIT	LONGITUDINAL ORIENTATION			TRANSVERSE ORIENTATION		
		SURFACE LOCATION	QUARTER THICKNESS LOCATION	MID THICKNESS LOCATION	SURFACE LOCATION	QUARTER THICKNESS LOCATION	MID THICKNESS LOCATION
Steel A	-40	PB,PB,PB	PB,PB,PB	PB,PB,PB	100,100,100	100,100,100	100,100,100
	-90	100,100,PB	PB,PB,PB	PB,100,100	100,100,100	100,PB,PB	100,PB,PB
	-120	91,90,90	100,100,PB	100,26,100	27,30,30,100	100,PB,100	100,PB,PB
	-140	90,90,90	90,90,90	PB,14,0,0	100,100,100	51,0,0	100,0,100
	-160	0,0,0	0,0,100	0,6,11	0,50,PB	3,0,0	0,0,69
Steel B	-40	100,100,100,80	100,100,100,100	100,100,100,90	50,100,69,65	77,51,60,65	82,66,65,100
	-50	100,100,100	59,62,80	100,100,100	72,72,70	60,61,56	66,65,76
	-60	100,100,62	62,75,75	70,69,64	63,62,56	59,50,50	70,69,70
	-90	45,45,45	50,51,45	50,57,45	60,60,60	66,40,70	56,56,40
	-120	18,29,0,0	0,0,0,4,2	29,29,0,35	33,27,30	21,27,27	35,20,20
	-140	0,10,10	0,3,10	0,10,33	39,30,39	26,30,26	5,26,35
	-160	0,0,0	0,0,0	0,0,0	0,0,0	3,10,0	0,0,0
Steel C	68	100,100,100	100,100,100	100,100,100	100,100,100	100,100,100	100,100,100
	0	100,100,100	100,100,100	100,100,100	100,100	100,100,100	100,100,100
	-40	100,90,90	100,100,100	100,100,100	100,100,100,100	100,100,100	100,100,100
	-90	75,69,76,70	69,80,84	90,92,100	66,47,55	65,79,71	61,69,68
	-120	36,33,45	50,73,54	43,68,42	27,0,14	30,25,30	33,39,45
	-180	0,0,0	0,16,0	10,20,23	5,5,3	14,3,0	10,3,14
	-240	0,0,0	0,0,0	0,0,0	0,0,0	0,0,0	0,0,0
Steel D	68	100,100,100	100,100,100	100,100,100	100,100,100	100,100,100	100,100,100
	0	100	100	100	100	100	100
	-20	77,100,90	100,100,100	100,100,100	44,73,60	100,100,100	100,100,100
	-40	69,77,100	100,100,100	50,100,100	50,50,59	90,80,100	100,100,100
	-50	66,66,69	69,100,100	67,100,100	47,34,39	56,65,74	66,65,58
	-90	54,55,66	58,63,51	61,55,59	35,27,30	42,39,52	59,62,39
	-120	27,5,30	30,44,34	33,39,39	0,0,10	34,40,39	39,47,30
	-180	3,0,0	10,0,0	6,0,0	0,0,0	0,5,0	0,0,0
	-240	0	0	0	0	0	0

PB = Partial break.

TABLE D6

DROP WEIGHT DYNAMIC TEAR TEST DATA

SAMPLE	TEST TEMPERATURE, IN DEGREES C	ENERGY ABSORBED IN FOOT-POUNDS
STEEL A	-60	PB
	-70	112; PB
	-80	62
STEEL B	-20	PB
	-40	802
	-60	597
	-70	382
	-80	17
STEEL C	-20	PB
	-40	1,107; PB
	-50	PB
	-60	332; 50
	-70	117
	-80	237
STEEL D	0	PB
	-20	557
	-40	404
	-60	72
	-80	42

PB = Partial break

TABLE D7

THROUGH THICKNESS HARDNESS SURVEY

	STEEL A in RB*	STEEL B in RB*	STEEL C in RC*	STEEL D in RC*
SURFACE	95	98,98	21	26
DEPTH BELOW SURFACE, in sixteenths of an inch				
1	98	98,98,100;RC20	22,24	27,28
3	95	98,98,98;RC18	22	28
5	95	96,99	23	28
7	95	96,98	22	28
9	96	97,100	22	29
	CL			
11	94	97,99	22	26
13	95	97,98	22	25
15	94	97,98	20	24
		CL	CL	CL
17	93	97,98	20	24
19	94,96;RC14	97,98	22	26
21	-	97,100	22	27
23	-	96,96,102	21	28,28
25	-	97,102	22	28,28
27	-	98,103	22	28
29	-	100,105	22	28
31	-	99,102;RC26,27	22	28
SURFACE	96	98,98;BHN229	27	25

*in hardness scale noted unless otherwise indicted
R_B = Rockwell B scale
R_C = Rockwell C scale
BHN = Brinell Hardness number
CL = Plate Centerline

APPENDIX E

WELDING PARAMETERS

TABLE E1
WELDING PARAMETERS FOR CTS TEST

Process	Shielded Metal Arc Welding
Filler	AWS A5.5, E11018M
Filler Diameter	5/32"
Position	Flat (1F)
Joint	Fillets
Preheat	None ((RT)
Polarity	Direct Current Reverse Polarity
Current	110-120 Amps
Voltage	22-23 Volts
Technique	Stringer
Bead Sequence	Single Pass
Travel	5-7 inches/minute
Heat Input	21-33 KJ/inch

TABLE E2

WELDING PARAMETERS FOR SMALL SCALE TEST WELDMENT

	STEEL A	STEEL C
Process	SMAW	SMAW
Filler Metal	AWS A5.5, E9018M	AWS A5.5, E11018M
Root Passes Diameter	1/8"	1/8"
Fill Passes Diameter	5/32"	5/32"
Position	Flat (1G)	Flat (1G)
Joint, as per AWS D1.1	B-U5a*	B-U5a*
Preheat	None (RT)	None (RT)
Interpass	200F	200F
Polarity	DCRP	DCRP
Current		
Root Passes	120-130 amps	120-130 amps
Fill Passes	150-160 amps	150-160 amps
Voltage	19-22 volts	19-22 volts
Technique	Stringer Only	Stringer Only
Bead Sequence	Multipass/Split Layer	Multipass/Split Layer
Travel Speed	5-6 in/minute	5-6 in/minute
Heat Input		
Root Passes	23-34 KJ/in.	23-34 KJ/in.
Fill Passes	28-42 KJ/in.	28-42 KJ/in.
Back Gouge	Yes	Yes

*Double Bevel Groove Butt Joint; square side of "K" used for fusion line and HAZ study